

CP VIOLATION: THE PAST AS PROLOGUE

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ABSTRACT

CP violation is now measured by three numbers: ϵ and ϵ' for the K^0 system and $\sin 2\beta$ for B^0 . A future measurement of the analogue of ϵ' for the B system would end any possibility of a Superweaklike Theory. Future frontiers in CP violation are briefly discussed.

1 ϵ and ϵ' for the K^0 System

C, P, and T have played a major role in particle physics over the last fifty years. I like to say that these were theoretical discoveries, not postulates. The starting point was assumed Hamiltonians, in particular QED, which were found to have these symmetries. When Fermi invented the weak interaction in 1933, he modeled it after QED and so it had these symmetries, although this was not emphasized for a long time.

In the 1950's it was pointed out that it was easy to invent interactions that violated these symmetries. However, every local relativistic interaction was found to be invariant under C times P times T. Thus, when P violation was found in 1957, the V-A interaction that explained it violated P and C but left CP and T invariant.

Then in 1964, CP violation was discovered in the decay $K_L \longrightarrow 2\pi$. Thirty-six years later the only CP or T violation known was in the K^0 systems. Now we have the first observation of CP violation in the B^0 system.

The first observation could be explained as due to CP violation in $K^0 - \overline{K}^0$ mixing. If we set $\overline{K}^0 = CP$ times K^0 then the CP eigenstates are

$$\begin{aligned} K_+ &= (K^0 + \overline{K}^0) / \sqrt{2} \\ K_- &= (K^0 - \overline{K}^0) / \sqrt{2} \end{aligned}$$

Then CP violation can result from a small term m' in the mass matrix; in the $K_+ - K_-$ representation

$$M = \begin{pmatrix} M_1 & im' \\ -im' & M_2 \end{pmatrix}$$

where the phase factor i is required by CPT invariance. Then the eigenstates are (to lowest order in ϵ)

$$\begin{aligned} K_S &= K_+ + \epsilon K_- \\ K_L &= K_- + \epsilon K_+ \\ \epsilon &= -im' (M_1 - M_2) - i(\Gamma_1 - \Gamma_2) / 22 \end{aligned} \tag{1}$$

The observed decay $K_L \longrightarrow \pi^+ \pi^-$ is then due to the component ϵK_+ in K_L :

$$\eta_{+-} = A(K_L \longrightarrow \pi^+ \pi^-) A(K_S \longrightarrow \pi^+ \pi^-) = \epsilon \tag{3}$$

with a magnitude 2×10^{-3} .

Twenty five years later, the magnitude of ϵ was the only quantity measuring CP violation. Another measurement, the lepton asymmetry in K_L decay, determined $\text{Re } \epsilon$ and there were independent measurements of φ_{+-} , the phase of η_{+-} , essentially equal to the phase of ϵ . However,

all these experiments did was to confirm CPT invariance, which already predicts very accurately from Eq. (2) the phase of ϵ

$$\varphi_\epsilon \approx \varphi_{+-} = \tan^{-1}(\Delta M/\Delta\Gamma)$$

Since ΔM and $\Delta\Gamma$ have nothing to do with CP violation, the value of φ_ϵ in no way is a measure of CP violation. As long as the only CP violation observed can be attributed to mixing and CPT invariance holds, all CP violation can be attributed to one real parameter, m' in the mixing matrix. Sometimes a fundamental distinction is made between CP violation just due to mixing, $\text{Re } \epsilon$, and CP violation involving interference between mixing and decay. However, since the phase of ϵ has nothing to do with the nature of CP violation, this distinction can be misleading.

After the discovery of CP violation it was pointed out that it could be explained by a very weak new interaction that changed strangeness by 2 units ($\Delta S = 2$) and violated CP. Such a four-fermion interaction could have a coupling G_{sw} equal to 10^{-10} to 10^{-11} times the Fermi constant G_F . This came to be called the superweak model.

A major development in weak interaction theory was the spontaneously broken gauge theory. With the discovery of neutral currents in 1973, this became the standard model of weak interactions. However, the theory had the same CP invariance as the (V-A) theory.

Various possible methods of extending the theory to allow CP violation were proposed. One of these was in one paragraph of a paper in the "Progress of Theoretical Physics" that few people read. It said that if there were six quarks instead of four (although the fourth quark c had not yet been detected) then it was possible to have CP violation. With the discovery of the b quark this became the standard Kobayashi-Maskawa Theory of CP violation.

To disprove the superweak model it was necessary to detect CP violation in the decay amplitude. This is done by looking for a difference between the CP violation for the final $\pi^0\pi^0$ state and that for $\pi^+\pi^-$. The parameter ϵ' is defined by

$$\begin{aligned}\eta_{+-} &= \epsilon + \epsilon' \\ \eta_{00} &= \epsilon - 2\epsilon' \\ \eta_{00} &\equiv A(K_L \longrightarrow \pi^0\pi^0) / A(K_S \longrightarrow \pi^0\pi^0)\end{aligned}\tag{2}$$

After 35 years of experiments at Fermilab and CERN, results have converged on a definitive non-zero result

$$\text{Re } (\epsilon'/\epsilon) = (18 \pm 3) \times 10^{-4}\tag{3}$$

While in principle ϵ could be attributed to CP violation in decay or mixing, ϵ' is unambiguously a measure of CP violation in decay, and thus represents the first evidence against superweak. However, the value of ϵ' is only 4×10^{-6} so that, while it is not inconsistent with the standard model, it could be explained by some very weak ($\sim 10^{-6}G_F$) new interaction.

2 ϵ and ϵ' for the B System

When it was discovered that the B had a relatively long lifetime and decayed primarily to charm it became apparent that the CKM matrix had a hierarchical form [1]. Elements V_{ij} could be expanded in even or odd powers of λ ($\lambda = \sin$ of the Cabibbo angle). In particular,

$$\begin{aligned}
V_{cb} &= A\lambda^2 + 0(\lambda^4) \\
V_{ub} &= A\lambda^3(\rho - i\eta) + 0(\lambda^5) = |V_{ub}|e^{-i\gamma} \\
V_{td} &= A\lambda^3(1 - \rho - i\eta) + 0(\lambda^5) = |V_{td}|e^{-i\beta}
\end{aligned} \tag{4}$$

Measurements of V_{cb} give A between .76 and .9. The parameter η is the source of CP violation. With this parameterization it became clear that large CP-violating effects could be found in B decays in contrast to K decays.

The phase of V_{td} , β , was expected to lie between 10 and 35 degrees given the value of η required to fit ϵ in the K system. Because $B - \bar{B}$ mixing was dominated by the box diagram with virtual t quarks, the mixing matrix M_{12} would be proportional to V_{td}^2 and so have the phase 2β . The time-dependent CP violation in $B(\bar{B}) \rightarrow \Psi K_s$ is then proportional to $\sin 2\beta$. This is the first CP-violating observable found in the B system. The large value [2] $\sin 2\beta = .73 \pm .06$ is consistent with the expectation of the standard model. I referred to this [3] as ϵ_B because its origin could be entirely CP violation in mixing and so could be blamed on a new superweak $\Delta B = 2$ interaction with $G(\bar{b} d \bar{b} d) \sim 10^{-7} G_F$.

The next goal in B physics should be the analog of ϵ' ; that is, a CP-violating effect that demonstrates CP violation in the $\Delta B = 1$ decay amplitude. In contrast to the value 4×10^{-6} in the K system, ϵ'_B should be of order unity. This measurement should then be the final blow to any superweaklike theory.

The CP-violating phase in the $b \rightarrow u$ transition has a phase γ relative to $b \rightarrow c$ transition (which is involved in $B \rightarrow \Psi K_s$). Allowed values of γ are large: $|\sin \gamma| > 12$. Thus, by measuring the CP-violating time-dependent asymmetry A_i in some decay $B \rightarrow X_i$ where X_i is a CP-eigenstate involving $b \rightarrow u$ we can define

$$\epsilon'_{B_i} = A_i - \sin 2\beta \tag{5}$$

The example most discussed is $X_1 = \pi^+ \pi^-$; considering only the tree approximation for the decay

$$\epsilon'_{B_1} = \sin 2(\beta + \gamma) - \sin 2\beta \tag{6}$$

As pointed out by Winstein, [4] this may accidentally equal zero for $\gamma = \pi/2 - 2\beta$. In fact, one expects a sizeable penguin contribution to this decay. Estimating this [5] one finds that ϵ'_{B_1} is close to zero for γ in the neighborhood of 50° . On the other hand, for $\gamma \sim 75^\circ$, $|\epsilon'_{B_1}|$ would be greater than 0.5.

Another possibility are experiments that measure $\sin(2\beta + \gamma)$; we define

$$\epsilon'_{B_2} = \sin(2\beta + \gamma) - \sin 2\beta \tag{7}$$

Unfortunately, for a fair range of expected values of γ , ϵ'_{B_2} is not very different from zero.

3 Long Term Frontiers for CP Violation

There are important issues about CP violation which will take many years to study and some of which may be impossible to resolve. These are briefly discussed in this section.

3.1 Precision CKM Physics

We want to know whether all CP violation can be explained by the CKM matrix or, alternatively, there are some detectable effects from new physics. For this purpose, we seek observables that can be analyzed with small theoretical errors. The first of these is $\sin 2\beta$ and the second we expect (hopefully from CDF) is

$$[\Delta M_d / \Delta M_s]^{1/2} = |V_{td} / V_{ts}| / \xi \quad (8)$$

ξ is a measure of $SU(3)$ violation given by a quenched lattice calculation [6] as $1.15 \pm .04$, but more theory is needed to get an unquenched value. These two will define a narrow region in the (ρ, η) plane, one that is derived entirely from $B - \bar{B}$ mixing. If there are new physics contributions to the mixing; for example, due to SUSY particles or extra Higgs bosons, then these will not be correct values of (ρ, η) . Thus, we want precision determinations based on decays to see if they are consistent. In particular, there are a variety of experiments aimed at determining γ from decays that involve the $b \rightarrow u$ transition. It should be emphasized that the main purpose of such experiments is not to measure γ , but to show consistency (or the lack of it) between the value from decay with that derived indirectly from mixing.

In addition to B decays, it is also important to use rare K decays. In particular, the decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ [7] provides an independent determination of η .

3.2 Electric Dipole Moments

Considering only the CP violation due to η the electric dipole moment of the neutron $d_n < 10^{-31} e - cm$ and that of the electron d_e is much less. Thus, any foreseeable non-zero measurement would be a signal of new physics. In the case of d_n , the result could be blamed on Θ_{QCD} , an arbitrary parameter in the standard model. A non-zero d_e would be clearly a signal of physics beyond the standard model.

3.3 CP Violation in Lepton Mixing

Lepton-quark symmetry suggests that there should be CP violation in lepton mixing analogous to CKM. Since the mixing is meaningless in the limit of zero neutrino masses, the mixing shows up only in neutrino phenomena. We now have strong evidence of neutrino mixing from neutrino oscillations. The hope for seeing CP violation is a comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in long baseline experiments. A major problem is that any CP violation is proportional to the element of V_{e3} , which may be zero. (V_{e3} is the ν_e component in the state 3 which is separated from the two others by $\Delta m^2 \sim 3 \times 10^{-3} eV^2$). Thus, a determination of V_{e3} must be the first priority of forthcoming experiments.

There are in fact two other phases (not present in the quark CKM matrix) for the case of Majorana neutrinos. These have an effect on neutrinoless double beta decay ($\beta\beta$), but they may be very hard to detect even if $\beta\beta$ is observed [8].

3.4 Fundamental Origin of CP Violation

From the point of view of the standard model there is nothing fundamental about CP invariance. It is violated everywhere it can be and it just turns out, given the gauge theory and the assumed

particle content, that the only CP violation is in the Yukawa couplings of fermions to Higgs bosons. Furthermore, although the Yukawa coupling can contain a number of phases, it turns out that only one phase is physically significant for quarks (and one for Dirac neutrinos), that given in the CKM matrix.

There is also one other parameter, called Θ_{QCD} , which must be set to a very small value less than 10^{-9} to fit limits on d_n . Both to explain the small value of Θ_{QCD} and in hope of a better understanding of CP violation there are proposals that CP is a fundamental symmetry at some high mass scale which is spontaneously broken. In such theories, Θ_{QCD} is calculable and presumably non-zero at some loop level. It is possible that η is also calculable and leads to the standard model [9]. Alternatively, most CP violation could be due to new physics if η turned out to be too small [10].

It is hard to know whether questions such as these will ever be answered.

3.5 Baryon-antibaryon Asymmetry

A major hope much discussed in this conference is that somehow CP violation at some high mass scale effective in the early universe may lead to the predominance of baryons over antibaryons in the present universe. It is clear that this requires some CP violation beyond the standard model. Like so many cosmological problems, we do not know whether there is some fundamental answer or whether this is just a peculiarity of our universe associated with some chaotic birth pangs.

Acknowledgments

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